

# Transverse momentum resummation for Higgs boson searches

Pavel Nadolsky

Argonne National Laboratory

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1.  $\gamma\gamma$  production at the Tevatron and LHC  
(QCD background for  $H_{SM}^0 \rightarrow \gamma\gamma$  at the LHC)
2.  $b\bar{b} \rightarrow \text{Higgs}$  in Standard Model and MSSM

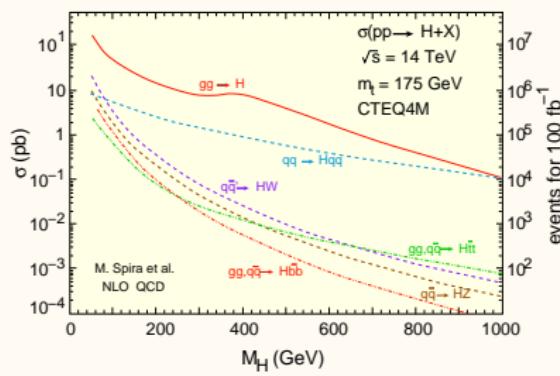
# $\gamma\gamma$ production at the Tevatron and LHC

## References

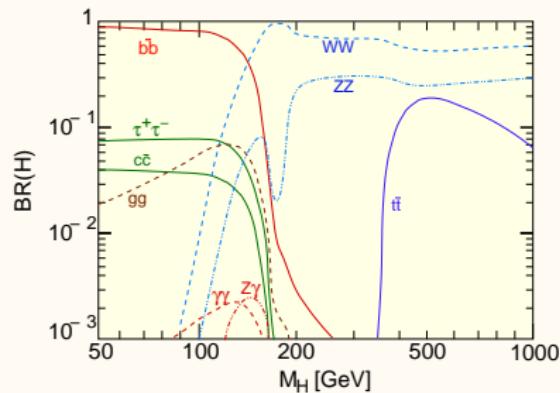
1. C. Balázs, E. Berger, **P. N.**, C.-P. Yuan, *hep-ph/0603037*
2. C. Balazs, E. Berger, S. Mrenna, C.-P. Yuan,  
*PRD 57*, 6934 (1998)
3. C. Balazs, **P. N.**, C. Schmidt, C.-P. Yuan,  
*PLB 489*, 157 (2000)
4. **P. N.**, C. Schmidt, *PLB 558*, 63 (2003)

# SM Higgs boson searches at the LHC

Production rate



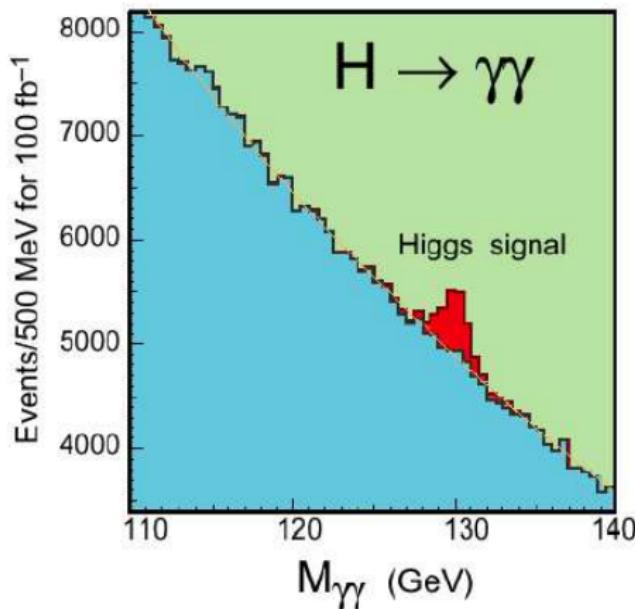
Branching ratios



- $gg \rightarrow H \rightarrow \gamma\gamma$  (via  $t$ -quark loop) is a promising search mode for  $115 < M_H < 140$  GeV
  - ▶ “low” QCD backgrounds

# SM Higgs signal and background

## Invariant mass ( $Q$ ) distributions



Assuming  $\mathcal{L} = 100 \text{ fb}^{-1}$ ,  
 $M_H = 130 \text{ GeV}$ ,  
at NLO (NNLO?):

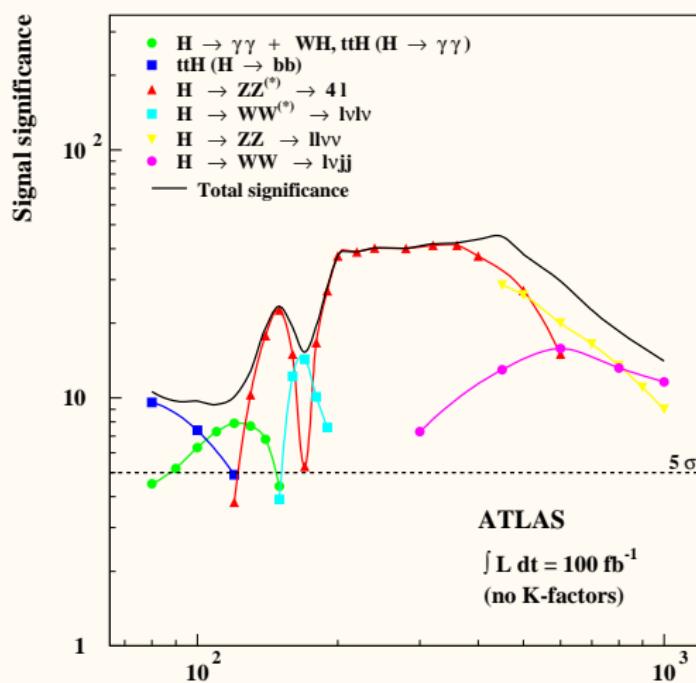
$$S/\sqrt{S+B} \sim 7 - 8$$

(statistics only!)

(Spira et al.; Dawson, Kauffman; Harlander, Kilgore; Anastasiou, Melnikov, Petriello; Bern, Dixon, Schmidt)

# SM Higgs signal and background

## Invariant mass ( $Q$ ) distributions



ATLAS physics  
performance study:

7 – 8 $\sigma$  discovery is feasible by observing a combination of  $\gamma\gamma$ ,  $WH$ ,  $t\bar{t}H$  decay channels

relies on  $Q$  resolution  
 < 1 GeV

# Transverse momentum distribution of diphotons ( $d\sigma/dq_T$ )

- Must be understood both for Higgs discovery and measurement of the Higgs cross section
- Event modeling, triggering, acceptance, efficiencies depend on  $q_T$
- Many observables depend on  $d\sigma/dq_T$  because of acceptance cuts
  - ▶  $d\sigma/dQ$  depends on  $d\sigma/dq_T$  due to acceptance cuts on  $p_T^\gamma$ , as already seen at the Tevatron

# Cuts on $q_T$ optimize the Higgs search

- Higgs signal significance is increased by selecting

$q_T \gtrsim 20 \text{ GeV}$  (*Abdullin et al., 1998; Balazs, PN., Schmidt, Yuan; de Florian, Kunszt, 1999; Berger, Qiu, 2003*)

- At  $q_T \ll Q$ ,

$$\left( \frac{d\sigma}{dq_T^2} \right)_{q_T^2 \ll Q^2} \approx \sum_{k=0}^{\infty} \alpha_s^k \left[ c_k \delta(\vec{Q}_T) + q_T^{-2} \cdot \sum_{n=0}^{2k-1} d_{nk} \ln^n(Q^2/q_T^2) \right];$$

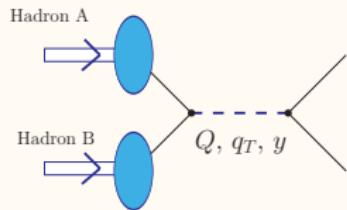
the large terms are summed to all orders in  $\alpha_s$  by means of Collins-Soper-Sterman (CSS) resummation

- $q_T$  resummation: Higgs signal has a larger  $\langle q_T \rangle$  than the background

# Cuts on $q_T$ optimize the Higgs search (cont.)

- Theory predictions are most reliable for  $E_T^{iso} \lesssim q_T \lesssim Q$   
( $E_T^{iso}$  is the photon isolation energy)
  - ▶ photon fragmentation and other large corrections are enhanced at  $q_T < E_T^{iso}$  or  $q_T \gtrsim Q$ !

# Transverse momentum ( $q_T$ ) resummation



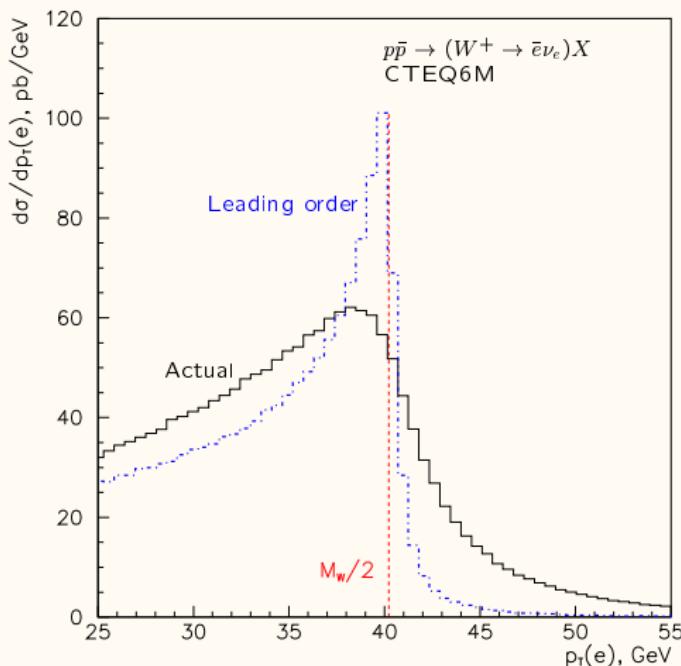
- an analytical method to compute normalization and shape of differential distributions in Drell-Yan-like processes
- hadron colliders:  
 $\gamma^*, W, Z, \text{Higgs}, \gamma\gamma, ZZ, \Upsilon, \dots$  production
- $e p$  colliders:  
semi-inclusive DIS, transverse spin asymmetries
- $e^+ e^-$  colliders: jet shapes

# Features of $q_T$ resummation

- neither a finite-order calculation nor a Monte-Carlo showering simulation!
- is proved by an all-orders factorization theorem in Drell-Yan-like processes
- resums all logs  $\alpha_s^k \ln^n(q_T^2/Q^2)$  at  $q_T^2 \ll Q^2$ ; reduces to the finite-order QCD cross sections at  $q_T \approx Q$ 
  - ▶  $\mathcal{O}(\alpha_s)$ /NLO  $q_T$  resummation formulated in 1979-1998
  - ▶ modern  $q_T$  resummation approaches NNLO accuracy
- nonperturbative corrections to  $d\sigma/dq_T$  are related by universality in different processes
- includes spin correlations in decays of heavy bosons

# $q_T$ resummation for $\gamma^*$ , $W$ , and $Z$ production (a classic example)

# Example: $d\sigma/dp_T^e$ in $p\bar{p} \rightarrow W \rightarrow e\nu X$



- Precise predictions for  $d\sigma/dq_T$ ,  $d\sigma/dp_T^e$ , and  $d\sigma/dp_T^\nu$
- Controls a leading systematic error in precision measurement of the  $W$  boson mass

# $q_T$ resummation in impact parameter ( $b$ ) space

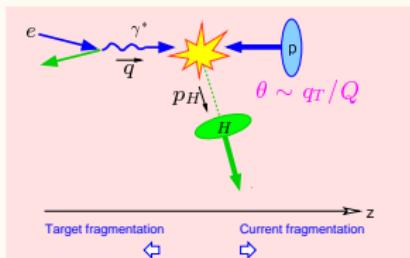
(Parisi, Petronzio, 1979; Collins, Soper, Sterman, 1981-1985)

- proved by a factorization theorem  
(J. Collins, A. Metz, 2004; X. Ji, J.-P. Ma, F. Yuan, 2004)
- applies to Drell-Yan-like processes (including  $\gamma\gamma$ ), SIDIS, and  $e^+e^-$  hadroproduction
- $d\sigma/dq_T$  are given by products of universal functions with perturbative and nonperturbative components

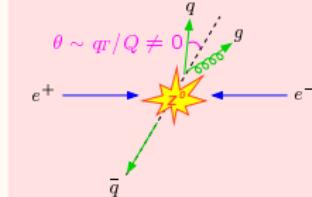
Vector boson production  
at the Tevatron



Semi-inclusive DIS in  
the  $\gamma^*p$  c.m. frame at HERA

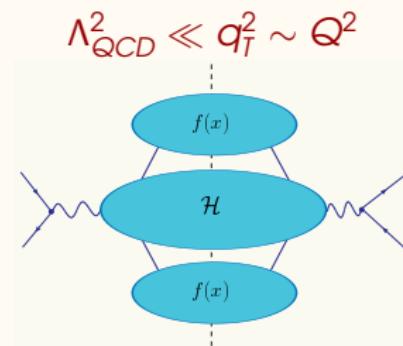


$e^+e^-$  hadroproduction  
at LEP

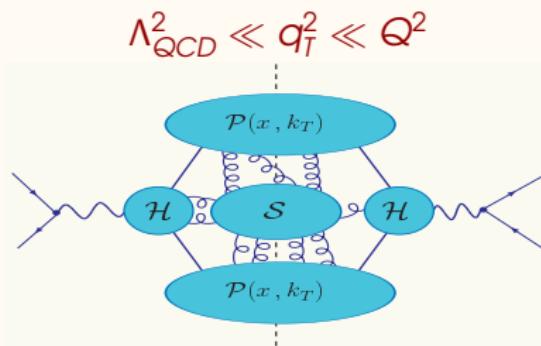


# QCD factorization in hard and soft regions

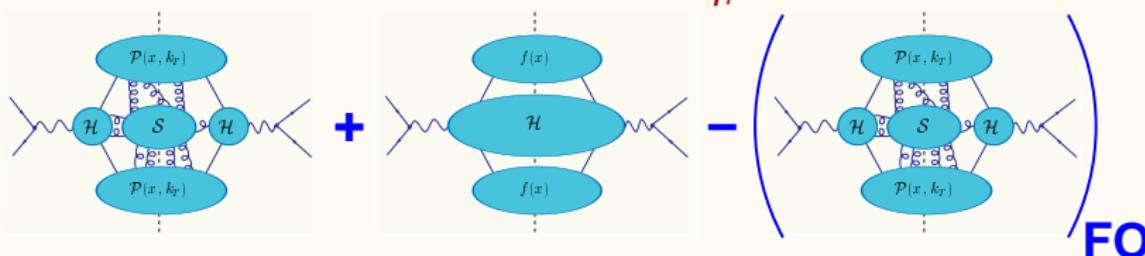
Finite-order (FO) factorization



Small- $q_T$  factorization



Solution for all  $q_T$ :



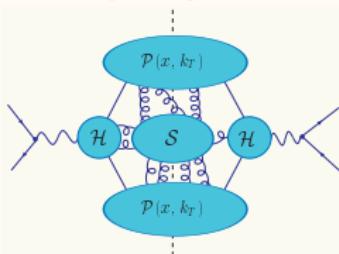
# Factorization at $q_T \ll Q$

Realized in space of the impact parameter  $b$

$$\frac{d\sigma_{AB \rightarrow V X}}{dQ^2 dy dq_T^2} \Bigg|_{q_T^2 \ll Q^2} = \sum_{\text{flavors}} \int \frac{d^2 b}{(2\pi)^2} e^{-i\vec{q}_T \cdot \vec{b}} \widetilde{W}_{ab}(b, Q, x_A, x_B)$$

$$\widetilde{W}_{ab}(b, Q, x_A, x_B) = |\mathcal{H}_{ab}|^2 e^{-S(b, Q)} \overline{\mathcal{P}}_a(x_A, b) \overline{\mathcal{P}}_b(x_B, b)$$

$\mathcal{H}_{ab}$  is the hard vertex,  $S$  is the soft (Sudakov) factor,  
 $\overline{\mathcal{P}}_a(x, b)$  is the unintegrated PDF



$$\overline{\mathcal{P}}_a(x, b) = \int d^{n-2} \vec{k}_T e^{i\vec{k}_T \cdot \vec{b}} \mathcal{P}_a(x, \vec{k}_T), \text{ with}$$

$$\mathcal{P}_a(x, \vec{k}_T) \sim \int \frac{dy^- d\bar{y}_T}{(2\pi)^3} e^{ixp_A^+ y^- - i\vec{y}_T \cdot \vec{k}_T} \langle p_A | \psi(y) \frac{\gamma^+}{2} \psi(0) | p_A \rangle$$

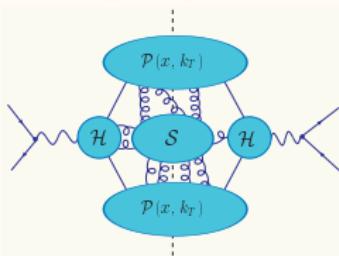
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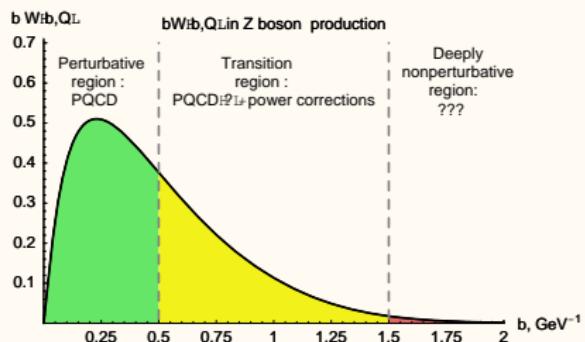
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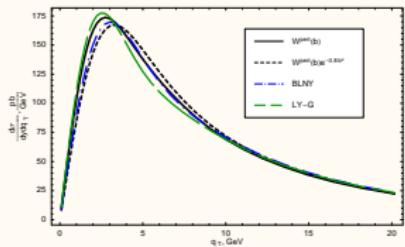
For  $b \ll 1 \text{ GeV}^{-1}$ ,  $S(b, Q)$  and  $\bar{\mathcal{P}}_a(x, b)$  are calculable in perturbative QCD;  
 $\bar{\mathcal{P}}_{a/A}(x, b) = (\mathcal{C}_{ja} \otimes f_{a/A})(x, b; \mu_F) + \mathcal{O}(b^2)$

# $b\tilde{W}(b, Q)$ in $W$ and $Z$ boson production



■  $b \lesssim 0.5 \text{ GeV}^{-1}$  :  
 $\tilde{W}(b, Q) \approx \tilde{W}_{\text{pert}}(b, Q)$   
 contributes most of the rate at  
 the Tevatron and LHC

■  $0.5 \lesssim b \lesssim 1.5 - 2 \text{ GeV}^{-1}$  :  
 higher-order terms in  $\alpha_s$  and  $b^p$   
 modify  $d\sigma/dq_T$  at  $q_T < 10 \text{ GeV}$



- important for  $M_W$  measurements;  
 constrained by a global  $q_T$  fit to  
 low- $Q$  Drell-Yan and  $Z$  boson data
- $b \gtrsim 1.5 - 2 \text{ GeV}^{-1}$  : terra incognita;  
 tiny contributions

Back to  $\gamma\gamma$  production...

# Prompt diphoton production

## Definition

Prompt photons = photons produced directly in perturbative QCD scattering or via parton fragmentation

as opposed to nonperturbative photon production in  $\pi$ ,  $\eta$  decays, etc. (suppressed by isolation)

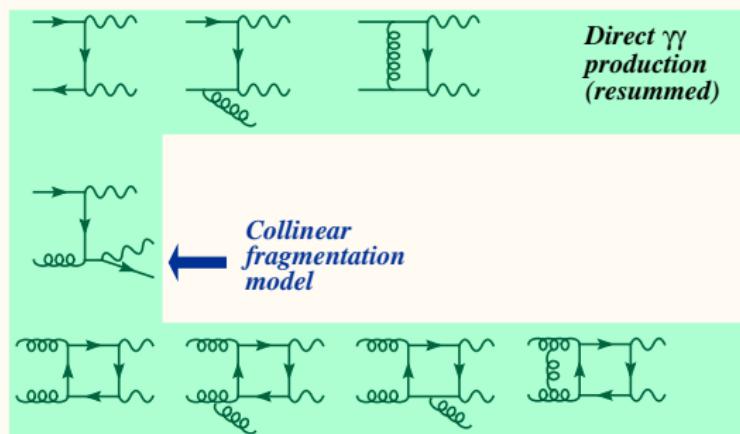
Prompt diphotons are produced by several processes with distinct kinematical distributions

- direct production
- single-photon fragmentation
- diphoton fragmentation

# 1. Direct diphotons

The dominant production mode; evaluated here up to full NLO/NNLL accuracy (MC integrator ResBos)

Balazs, Berger, Nadolsky, Yuan, 2006



- *qg and gg*  
channels are enhanced at  $x \sim Q^2/s \ll 1$  by large gluon PDF
- *qq}* and *qg* channels at NLO:  
Aurenche et al.; Bailey, Owens, Ohnemus
- *gg* channel at NLO:  
Balazs, PN, Schmidt, Yuan; de Florian, Kunzst; Bern, De Freitas, Dixon; Bern, Dixon, Schmidt

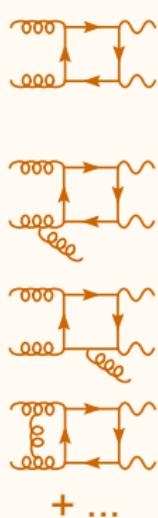
# New in 2006

- full NNLL accuracy in  $q\bar{q}$ ,  $qg$ , and  $gg$  channels
  - ▶ resummed  $\mathcal{O}(\alpha_s^3)$  contributions in  $gg \rightarrow \gamma\gamma X$
  - ▶ leading NNLO corrections to small- $q_T$  cross sections in all channels
- improved treatment of the fragmentation region
  - ▶ fragmentation negligible? important at the Tevatron?  
dangerous at the LHC?
- New model for nonperturbative resummed contributions (*A. Konychev, P. N., PLB 633, 710 (2006)*)
- automated matching; optimized Monte-Carlo integration

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# $gg \rightarrow \gamma\gamma X$ in the $q_T \ll Q$ limit



$\mathcal{O}(\alpha_s^3)$  1-loop 5-leg (pentagon) diagrams

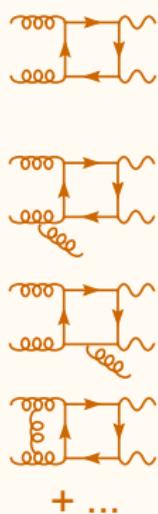
- are computed in the helicity amplitude formalism (1999)

- numerically agree with the “sector decomposition” calculation  
*(Binoth, Guillet, Mahmoudi, 2003)*

- Small- $q_T$  limit is derived at the matrix-element level with the splitting amplitude method  
*(Bern, Chalmers, Dixon, Dunbar, Kosower)*

- **Soft singularities** are cancelled against 2-loop box diagrams

## $gg \rightarrow \gamma\gamma X$ in the $q_T \ll Q$ limit

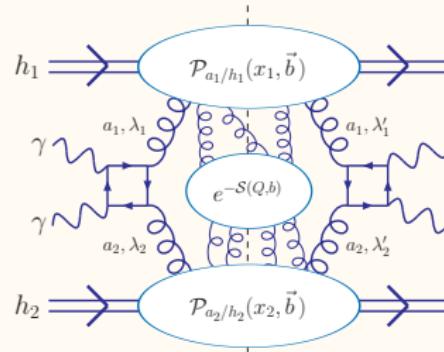


**Collinear singularities** arise due to radiation off an incoming gluon line

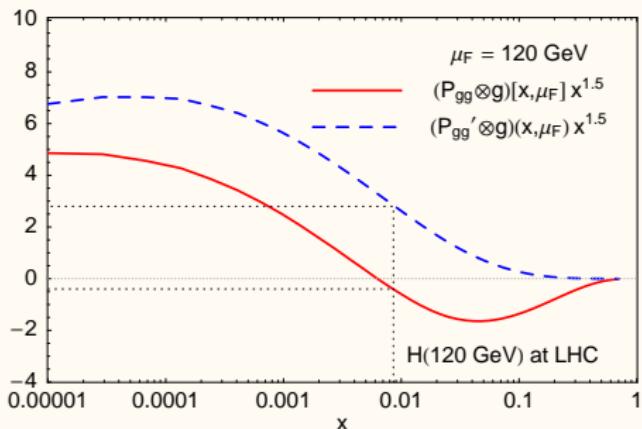
- usual collinear singularities (diagonal in helicity basis) are resummed in the gluon PDF's
- A new "off-diagonal"  $k_T$ -dependent gluon PDF is needed due to interference of box diagrams for different helicities
  - ▶ affects azimuthal angle ( $\varphi_*$ ) dependence in  $\gamma\gamma$  rest frame

# Spin correlations between hard vertices ( $gg\gamma\gamma$ boxes)

- In conventional PDF's  $\bar{P}_a(x, b)$ , parton helicities are the same on both sides of the unitarity cut ( $\lambda = \lambda'$ )
- In  $gg \rightarrow \gamma\gamma$ , contributions with  $\lambda = -\lambda'$  are present
- Such interference terms contribute with a factor  $\cos 2\varphi_*$  ( $\varphi_*$  is the azimuthal angle between the planes of the hadrons' and photons' momenta in the Collins-Soper  $\gamma\gamma$  rest frame)
  - ▶ they need not be small; mix with conventional  $\bar{P}_a(x, b)$  under RG evolution; must be resummed in new PDF's  $\bar{P}'_a(x, b)$



# DGLAP evolution of $\bar{P}_a(x, b)$ and $\bar{P}'_a(x, b)$



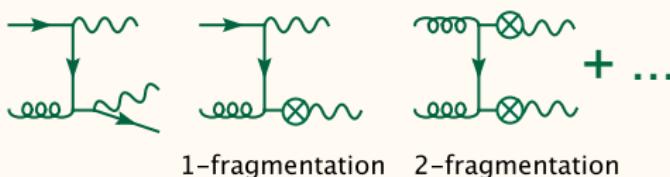
■  $(\mathcal{P}'_{gg} \otimes g)(x, \mu_F) > (\mathcal{P}_{gg} \otimes g)(x, \mu_F)$

Scaling violation in  $\bar{P}'_a(x, b)$  due to mixing with gluon PDF  $g(x, \mu_F)$  is determined by  $(\mathcal{P}'_{gg} \otimes g)(x, \mu_F)$ , with  $P'_{gg}(x) = 2C_A(1-x)/x$

## 2. Single-photon fragmentation

- Collinear parton fragmentation into  $\gamma$ 's is described by single-photon fragmentation functions  $D_\gamma(z)$   
(⊗

Some lowest-order  
diagrams (direct,  
1- and 2-fragmentation):

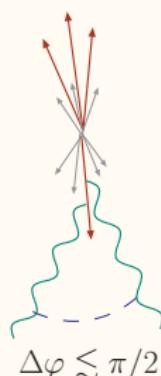


- DIPHOX program (*Binoth, Guillet, Pilon, Werlen*) Computes single- $\gamma$   
1- and 2-fragmentation contributions at NLO (no resummation!)

### 3. Low- $Q$ diphoton fragmentation

If  $Q < q_T$ ,  $\Delta\varphi = \varphi_{\gamma_1} - \varphi_{\gamma_2} < \pi/2$  in the lab frame:

- a  $\gamma\gamma$  pair may be produced entirely via fragmentation



- $\gamma\gamma$  fragmentation functions  $D_{\gamma\gamma}(z_1, z_2)$  (⊗) are needed
- cross section can be large at  $Q \ll q_T$
- no actual calculation exists yet (not in the computer codes!)

# Difficulties of fragmentation models I

- It is hard to reproduce experimental isolation in theory
  - ▶ a crude simplification: reject an event if the hadronic  $E_T > E_T^{iso}$  in a fixed angular cone around each photon ( $\Delta R = 0.3 - 0.7$ )
- Magnitude of fragmentation contributions depends on the isolation procedure
  - ▶ Fragmentation in DIPHOX depends strongly on the value of  $E_T^{iso}$
  - ▶ but which  $E_T^{iso}$  should be taken to compare with the data?

## Difficulties of fragmentation models II

- Collinear approximation and finite order in  $\alpha_s$ 
  - ▶ questionable light-cone ( $z$ ) and angular ( $\Delta R$ ) dependence of fragmentation radiation
  - ▶ integrable singularities at the edge of the isolation cone (*Berger, Quo, Qiu; Catani, Fontannaz, Pilon*)
  - ▶ discontinuities in  $d\sigma/dq_T$  at  $q_T \lesssim E_T^{iso}$

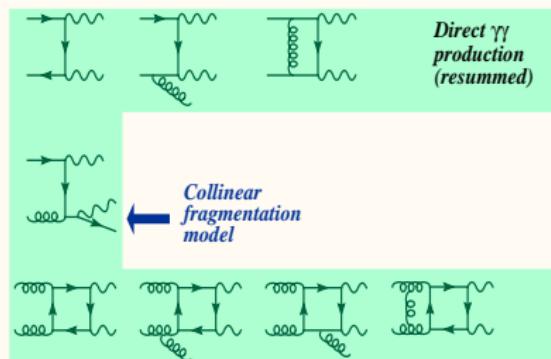
These issues need to be resolved in the future to obtain stable predictions for fragmentation

# Simplified fragmentation in ResBos

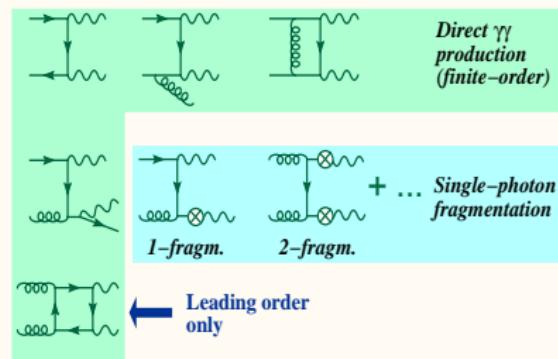
- Only direct production is included
- Cuts on the final-state parton (5) in the  $2 \rightarrow 3$  NLO term:
  - ▶  $q_T \geq E_T^{iso}$ : **quasi-experimental isolation**  
( $E_{T5} < E_T^{iso}$  for  $\Delta r < \Delta R$ )
  - ▶  $q_T < E_T^{iso}$ : **smooth-cone isolation**  
( $E_{T5} < E_T^{iso} \chi(\Delta r)$  for  $\Delta r < \Delta R$ )
- Integrable singularity at  $q_T = 0$   
(avoided in MC integration)
- no singularity at  $q_T = E_T^{iso}$
- mild dependence on the assumed  $\chi(\Delta r)$  at  $q_T < E_T^{iso}$

# Recap: implemented contributions

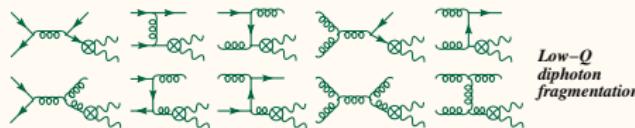
Balazs, Berger, Nadolsky, Yuan, 2006



Binotto, Guillet, Pilon, Werlen, 2001



Diphoton fragmentation (not implemented)



# Physics in different kinematical regions

$q_T < Q$  (or  $\Delta\varphi > \pi/2$  in the lab frame):

- largest cross section, dominated by resummed direct contributions
- reduced scale and isolation dependence
- some dependence on the fragmentation model at  $q_T < E_T^{iso}$

$q_T > Q$  (or  $\Delta\varphi < \pi/2$ ):

- small cross section
- enhanced fragmentation
- small  $|\eta_{\gamma_1} - \eta_{\gamma_2}|$ : low- $Q_{\gamma\gamma}$  fragmentation (not included)
- large  $|\eta_{\gamma_1} - \eta_{\gamma_2}|$ : large corrections with  $\cos\theta_* \approx \pm 1$  in  $\gamma\gamma$  rest frame (not included)
- large scale and isolation dependence

## Kinematical cuts

Isolation is much tighter at the Tevatron than at the LHC  
Tevatron Run-2

- $p_{T\gamma}^{hard} > 14 \text{ GeV}$ ,  $p_{T\gamma}^{hard} > 13 \text{ GeV}$ ,  $|\eta_\gamma| < 0.9$
- $E_T^{iso} = 1 \text{ GeV}$ ,  $\Delta R = 0.4$ ,  $\Delta R_{\gamma\gamma} = 0.4$

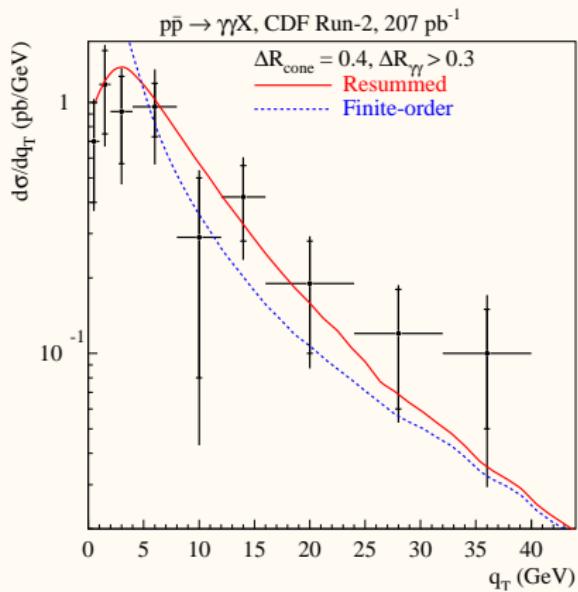
LHC

- $p_{T\gamma}^{hard} > 40 \text{ GeV}$ ,  $p_{T\gamma}^{hard} > 25 \text{ GeV}$ ,  $|\eta_\gamma| < 2.5$
- $E_T^{iso} = 15 \text{ GeV}$ ,  $\Delta R = 0.4$ ,  $\Delta R_{\gamma\gamma} = 0.4$

$\mu_F = \mu_R = Q$ ,  $\overline{MS}$  scheme

# Resummation vs. CDF Run-2 data

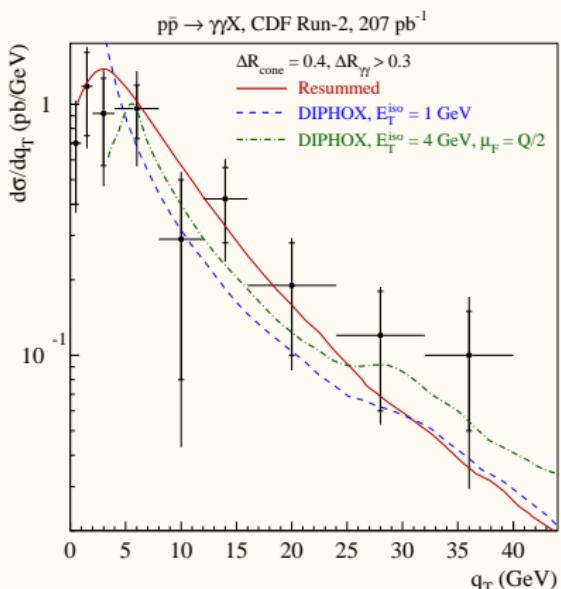
(PRL 95, 022003 (2005))



- The NLO prediction (blue) diverges at small  $q_T$
- The resummed prediction (red) agrees with the data at all  $q_T$ ; matches the NLO prediction at large  $q_T$

# Resummation vs. CDF Run-2 data

(PRL 95, 022003 (2005))



▲ for  $E_T^{\text{iso}} = 4 \text{ GeV}$ , the one-fragmentation cross section increases by 400%

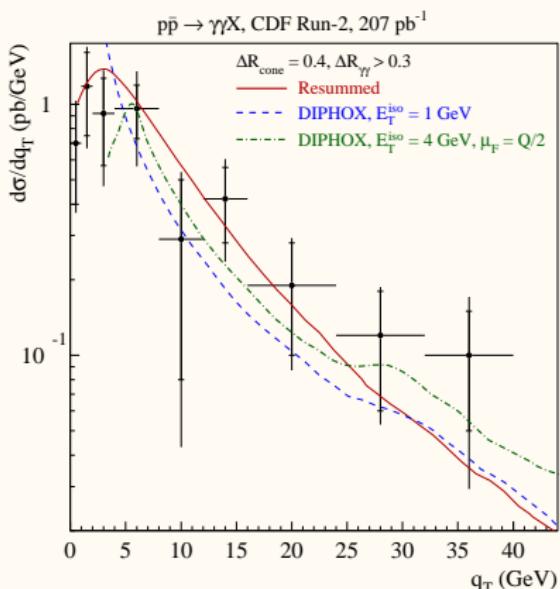
The large- $q_T$  “shoulder” occurs in the data at  $Q \lesssim 25 \text{ GeV}$ ,  $Q \lesssim q_T$

The DIPHOX cross section

- agrees with NLO RESBOS for the nominal  $E_T^{\text{iso}} = 1 \text{ GeV}$ , same  $\mu_F$
- reproduces the “shoulder” for  $E_T^{\text{iso}} = 4 \text{ GeV}$ , smaller  $\mu_F$

# Resummation vs. CDF Run-2 data

(PRL 95, 022003 (2005))



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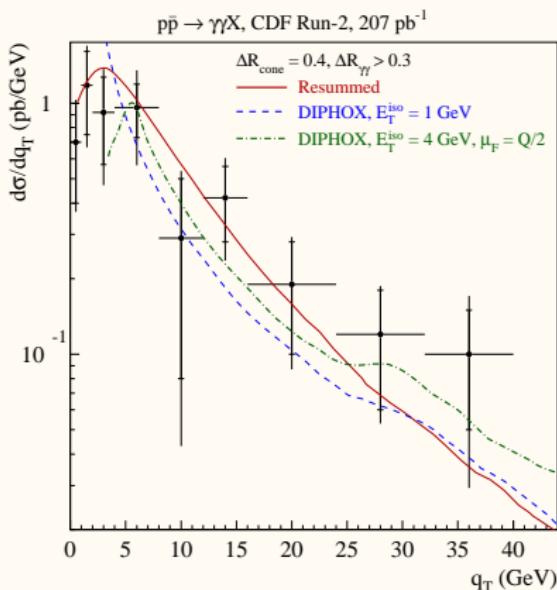
The DIPHOX cross section

- agrees with NLO RESBOS for the nominal  $E_T^{\text{iso}} = 1 \text{ GeV}$ , same  $\mu_F$

- reproduces the “shoulder” for  $E_T^{\text{iso}} = 4 \text{ GeV}$ , smaller  $\mu_F$

# Resummation vs. CDF Run-2 data

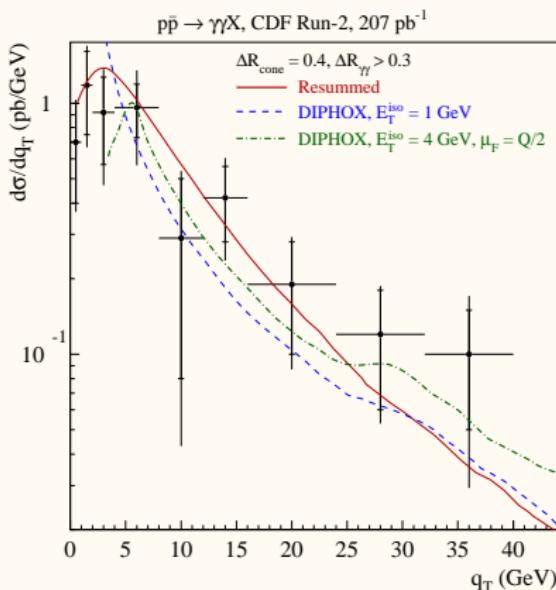
(PRL 95, 022003 (2005))



Other large corrections are known to contribute at  $Q \lesssim q_T$  (not in the existing theory calculations)

# Resummation vs. CDF Run-2 data

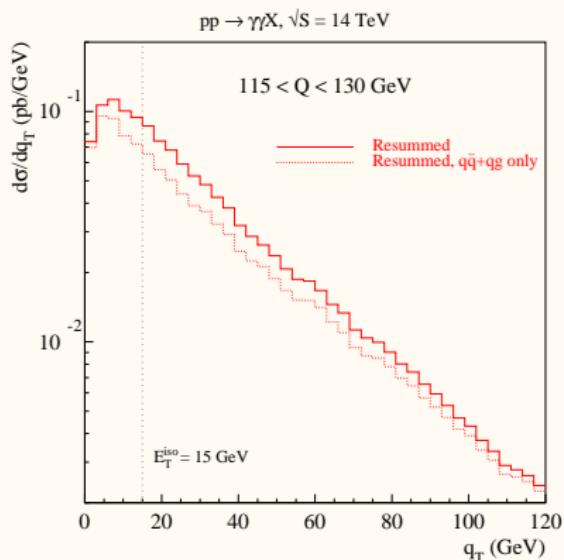
(PRL 95, 022003 (2005))



The CDF “shoulder” is a low- $Q$  effect, not relevant for the LHC Higgs searches

▲ can be removed by a  $q_T \leq Q$  cut

# $q_T$ distributions at the LHC

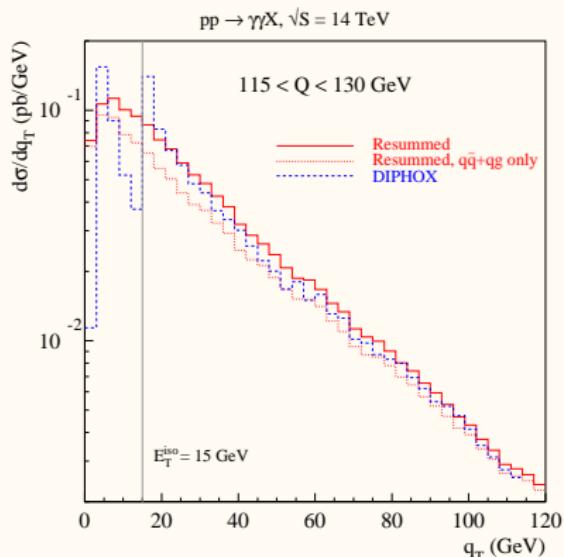


$$q\bar{q} : qg : gg = 30:50:20$$

(compare with  
 $q\bar{q} : qg : gg = 70:20:10$   
at the Tevatron)

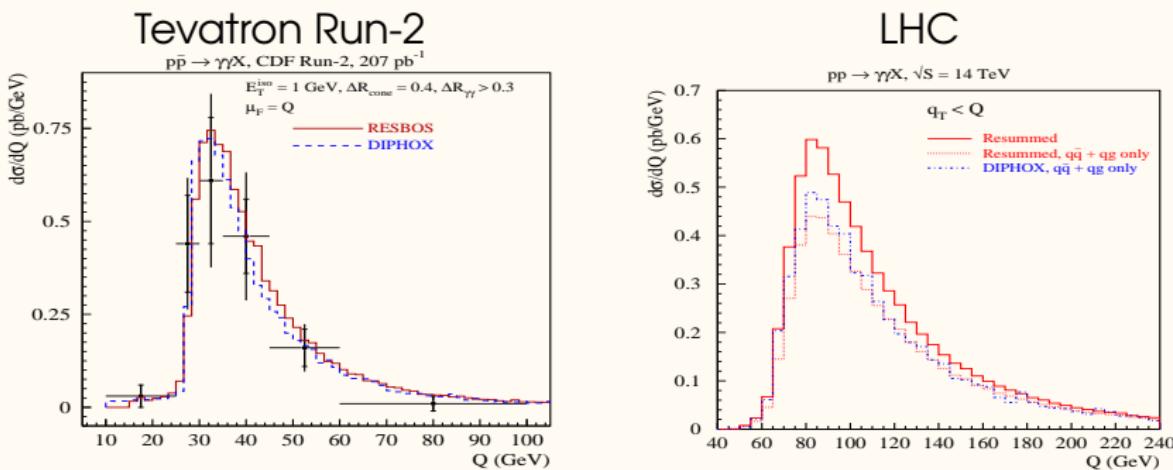
$\mathcal{O}(\alpha_s^2)$  corrections to  $qg$  are likely important  
 $(\sigma_{NNLO}/\sigma_{NLO} \sim 20\%?)$

# $q_T$ distributions at the LHC



- DIPHOX agrees with the resummation at large  $q_T$ ; exhibits integrable logarithmic singularities at  $q_T < E_T^{\text{iso}}$
- RESBOS shows a mild discontinuity at  $q_T = E_T^{\text{iso}}$

# Invariant mass distributions



- Good agreement between RESBOS and DIPHOX
  - ▶ dominance of direct contributions
  - ▶ dependence on  $d\sigma/dq_T$  because of the  $p_{T\gamma}$  cuts

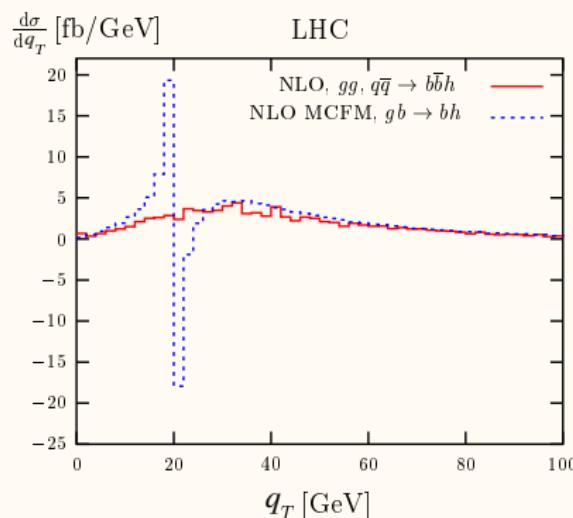
# Resummation for $b + \bar{b} \rightarrow H$ in SM and MSSM

$m_b \approx 4.5 \text{ GeV}$  is not negligible as  $q_T \rightarrow 0$ , or for factorization scales  $\mu \sim M_H/4 \lesssim 50 \text{ GeV}$

⇒ Neither 4-flavor number scheme nor massless 5-flavor number scheme are applicable at  $q_T \rightarrow 0$

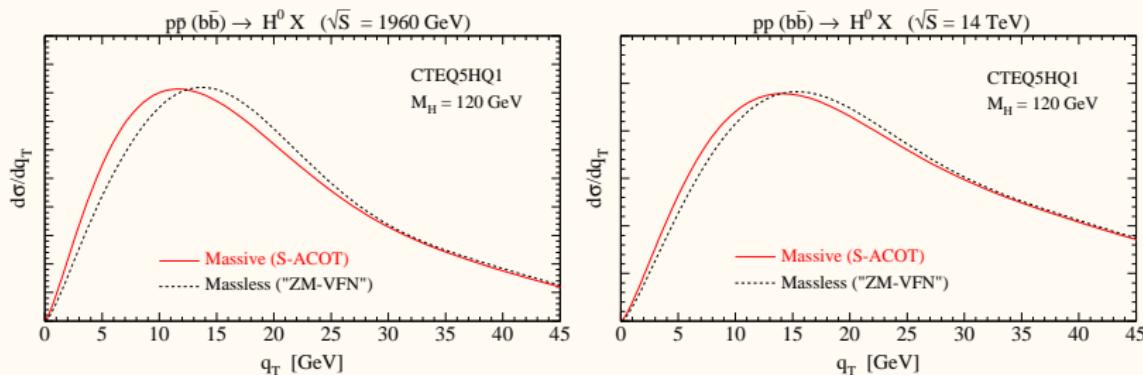
Solution:  $q_T$  resummation in a massive 5-flavor number scheme

(P.N., Kidonakis, Olness, Yuan, 2002;  
Berge, P.N., Olness, PRD 73, 013002 (2005); Belyaev,  
P.N., Yuan, JHEP 04 (2006) 004 )



Dawson, Jackson, Reina, Wackerlo, PRL 94, 031802  
(2005)

# $b\bar{b} \rightarrow H$ : variations in $d\sigma/dq_T$ due to $m_b$ effects



- Tevatron,  $M_H = 120$  GeV,  $\mu = M_H$ : the “ZM-VFN” peak is shifted by 2 GeV ( $\approx 17\%$ ) w.r.t. to the S-ACOT peak; more if  $\mu \sim M_H/4$
- Slightly smaller  $m_b$  dependence at the LHC

# What we have learned

- We computed the normalization and shape of  $d\sigma/d^3p_{\gamma_1}d^3p_{\gamma_2}$  for direct  $\gamma\gamma$  production at NNLL/NLO. Large logs are resummed at  $q_T \ll Q$ . At  $q_T \gtrsim Q$ , our results agree with NLO, DIPHOX calculation within the fragmentation model uncertainty.
- Theory predictions for QCD  $\gamma\gamma$  production are most reliable at  $E_T^{iso} < q_T < Q$ 
  - ▶ would be nice to have the experimental data presented in the same  $q_T$  interval!
- The shape of  $d\sigma/dq_T$  affects  $d\sigma/dQ$  and other observables; has an impact on  $H \rightarrow \gamma\gamma$  search

# Powerful predictions of $q_T$ resummation

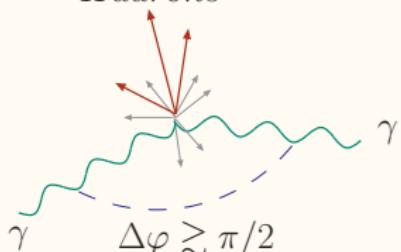
- a “spin-flip”  $k_T$ -dependent PDF describing  $d\sigma/dq_T d\varphi_*$  in unpolarized  $gg \rightarrow \gamma\gamma X$
- non-negligible dependence on  $b$ -quark mass in  $b\bar{b} \rightarrow H$  at small  $q_T$
- demonstration of universality of leading nonperturbative corrections
- $x$  dependence of  $q_T$  distributions  
(Berge, P.N., Olness, Yuan, PRD72, 033015 (2005))
  - ▶ enhanced BFKL-like corrections at  $x \lesssim 10^{-2}$  in  $W, Z$ , Higgs production at the LHC?

# Backup slides

# Direct diphotons: kinematical distributions

Transverse plane

*Hadrons*



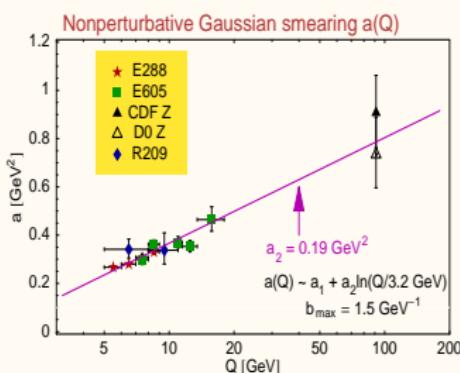
- Direct events mostly populate the region  $q_T \lesssim Q$ ,  
 $\Delta\varphi \equiv \varphi_{\gamma_2} - \varphi_{\gamma_1} \gtrsim \pi/2$  in the lab frame ( $0 \leq \Delta\varphi \leq \pi$ )
- Enhanced initial-state logarithmic corrections at  $q_T^2 \ll Q^2$ :

$$\left( \frac{d\sigma}{dq_T^2} \right)_{q_T^2 \ll Q^2} \approx \sum_{k=0}^{\infty} \alpha_s^k \left[ c_k \delta(\vec{Q}_T) + q_T^{-2} \cdot \sum_{n=0}^{2k-1} d_{nk} \ln(Q^2/q_T^2) \right]$$

⇒ finite-order PQCD unreliable  
 Solution: small- $q_T$  resummation!

# Universality of nonperturbative contributions

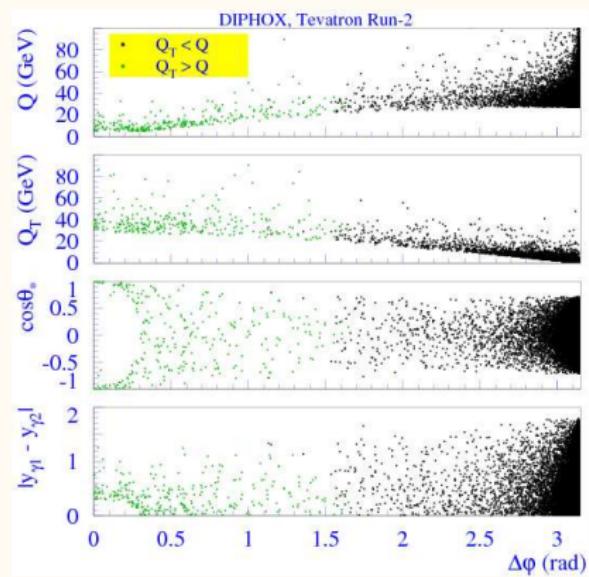
A. Konychev, *P. N.*, PLB 633, 710 (2006)



- $q_T$  factorization: initial-state nonperturbative contributions ( $\sim$  “intrinsic”  $\langle k_T^2 \rangle \equiv a$ ) follow universal quasi-linear dependence on  $\ln Q$ ; this expectation is confirmed by the global analysis of Drell-Yan and  $Z$  boson data

- the observed  $\ln Q$  dependence agrees with the renormalon/lattice estimate
- at  $Q \sim M_Z$ , soft NP corrections dominate over collinear NP corrections
- the model is employed to predict  $\gamma\gamma$  cross sections

# Event distributions

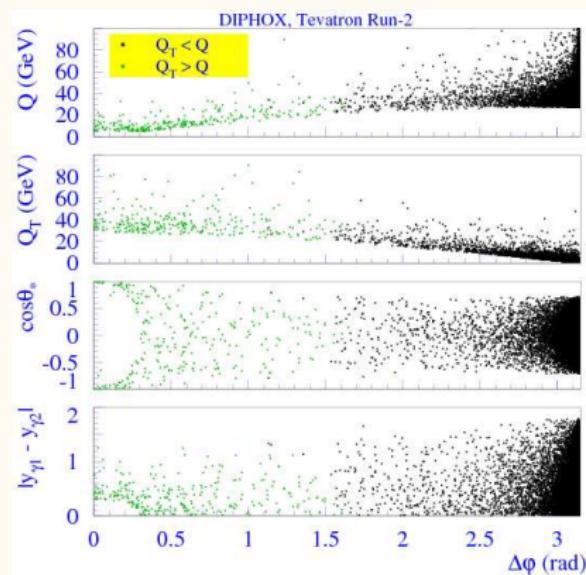


- The shoulder arises in a small kinematical region ( $Q \lesssim 27$  GeV,  $q_T \gtrsim 25$  GeV, and  $\Delta\varphi \leq \pi/2$ ) as a result of acceptance ( $p_T$ ) cuts imposed on  $\gamma$ 's

► here  $q_T \gtrsim Q$

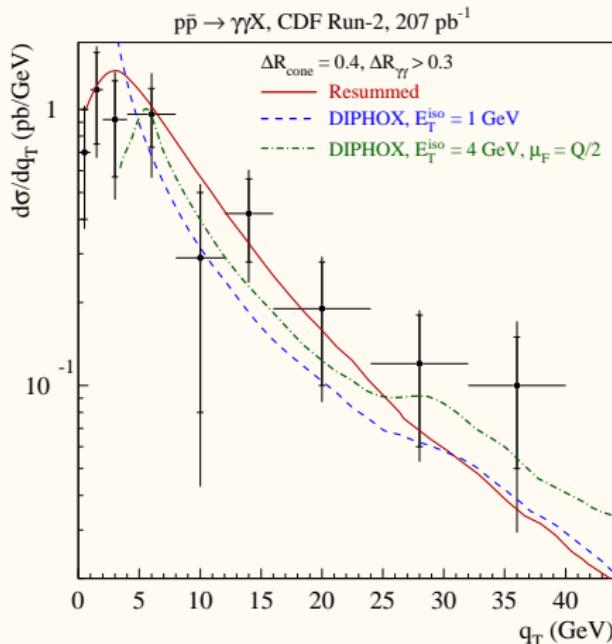
- At  $\Delta\varphi < 0.3$ , the cuts allow only events with  $|\cos\theta_*| > 0.5$  in the  $\gamma\gamma$  rest frame

# Event distributions

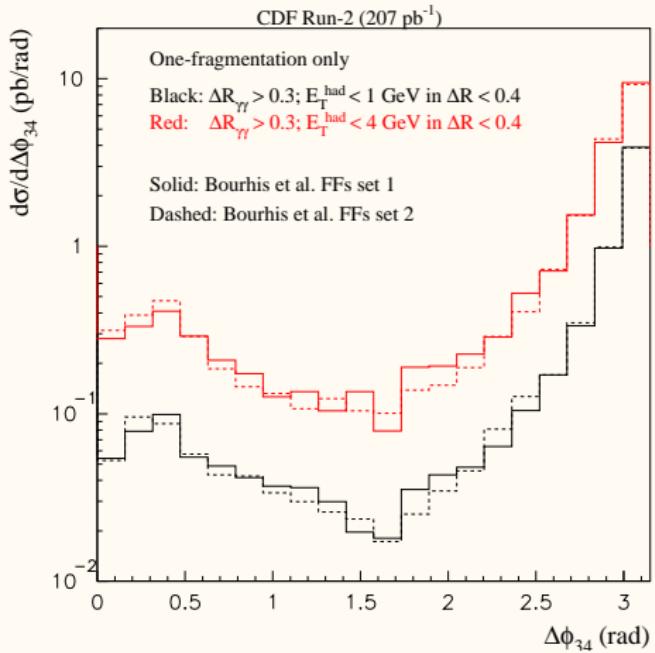


■ Higher-order corrections beyond the existing calculations surely contribute in the shoulder region

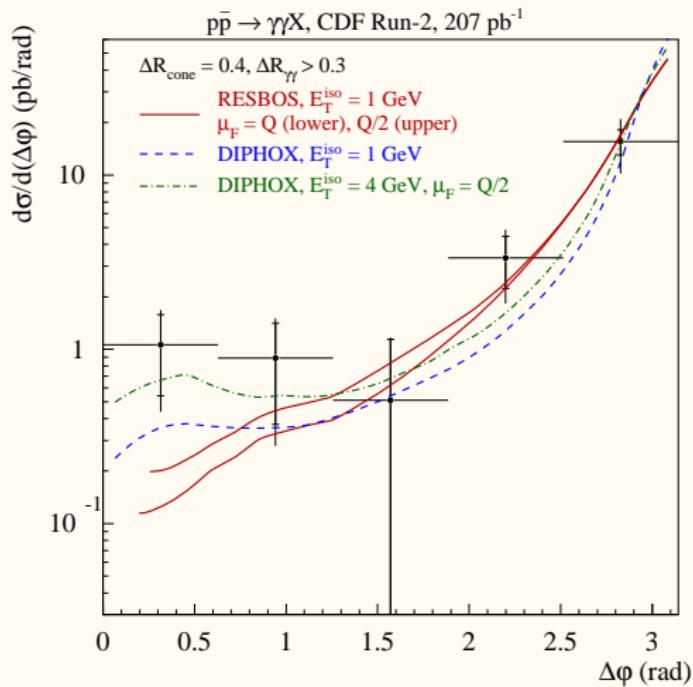
# Scale and $E_T^{iso}$ dependence



- For the nominal CDF value of  $E_T^{iso} = 1 \text{ GeV}$  and  $\mu_F = Q$ , DIPHOX
  - ▶ agrees well with NLO from RESBOS
  - ▶ underestimates the shoulder region
  
- One needs to choose  $\mu_F = Q/2$  and  $E_T^{iso} = 4 \text{ GeV}$ ...

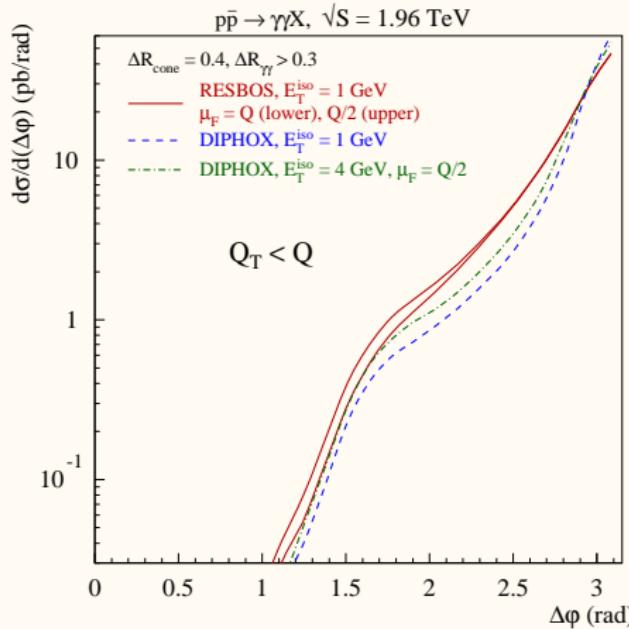


... to enhance 1-fragmentation contributions on average by 400%...



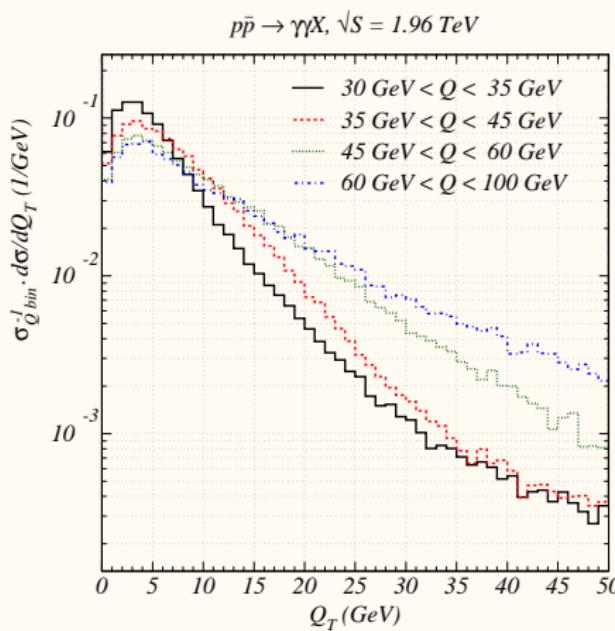
...and bring DIPHOX in agreement with the small- $\Delta\phi$  data

$q_T < Q \text{ cut}$



If only events with  $q_T < Q$  are selected, theory uncertainties are greatly reduced

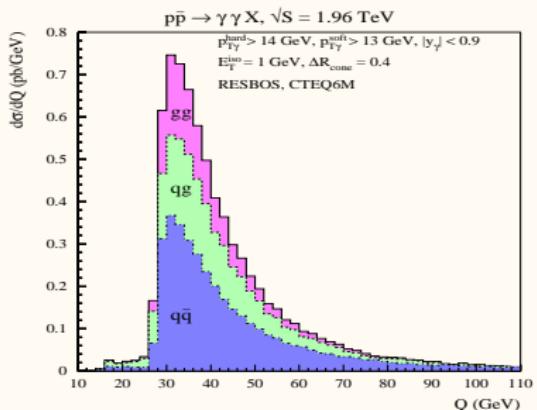
# Q dependence of $q_T$ distributions



- Resummation predicts that  $d\sigma/dq_T$  broadens as  $Q$  increases ( $\langle q_T \rangle$  grows)
- a measurement of  $d\sigma/dQ^2 dq_T^2$  in several bins of  $Q$  will be an instructive test of this prediction

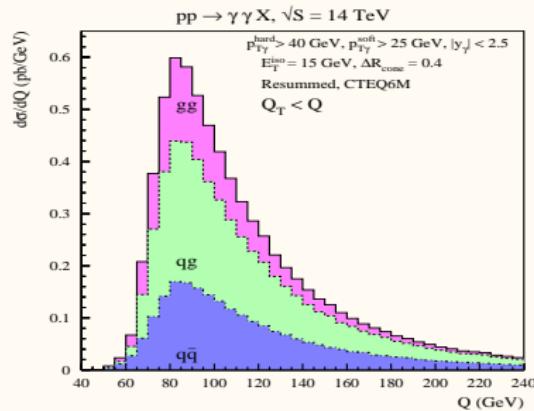
# From Tevatron to LHC: flavor composition of cross sections

## Tevatron Run-2



Leading channel:  $q\bar{q}$   
(50-70% of events)

## LHC



Leading channel:  $q\bar{q}$   
(40-55%); evaluated at LO!!!  
 $\mathcal{O}(\alpha_s^2)$  corrections  $\gtrsim 20\% (?)$